Supernova observation via neutrino-nucleus elastic scattering in the CLEAN detector

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Development of large mass detectors for low-energy neutrinos and dark matter may allow supernova detection via neutrino-nucleus elastic scattering. An elastic-scattering detector could observe a few, or more, events per ton for a galactic supernova at 10 kpc (3.1×10^{20} m). This large yield, a factor of at least 20 greater than that for existing light-water detectors, arises because of the very large coherent cross section and the sensitivity to all flavors of neutrinos and antineutrinos. An elastic scattering detector can provide important information on the flux and spectrum of ν_μ and ν_τ from supernovae. We consider many detectors and a range of target materials from ^{4}He to ^{208}Pb. Monte Carlo simulations of low-energy backgrounds are presented for the liquid-neon-based Cryogenic Low Energy Astrophysics with Noble gases detector. The simulated background is much smaller than the expected signal from a galactic supernova.

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I. INTRODUCTION

Rich information on neutrino properties, oscillations, the supernova mechanism, and very dense matter is contained in the neutrinos from core-collapse supernovae [1]. Existing detectors such as Super-Kamiokande [2] should accurately measure the $\bar{\nu}_e$ component of the supernova signal. However, the very interesting ν_μ, ν_τ, $\bar{\nu}_\mu$, and $\bar{\nu}_\tau$ (collectively ν_x) components may be detected without direct energy information and or in the presence of significant backgrounds from other neutrino induced reactions. Therefore, additional ν_x detectors could be very useful.

Perhaps the ''ultimate'' supernova detector involves neutrino-nucleus elastic scattering [3,4]. The count rate in such a detector could be very high because the coherent elastic cross section is large and all six neutrino components (ν_e, $\bar{\nu}_e$, and the four ν_x) contribute to the signal. In particular, the detector is sensitive to ν_x, which are expected to have a high energy and large cross section. Elastic scattering detectors can have yields of a few or more ν_x events *per ton* for a supernova at 10 kpc (3.1×10^{20} m). This is an increase by a factor of 20 or more over existing light-water detector yields of hundreds of $\bar{\nu}_e$ and tens of ν_x events *per kiloton*.

Furthermore, the energy of nuclear recoils provides direct information on the ν_x spectrum. Existing detectors measure ν_x via neutral-current inelastic reactions on oxygen [5], deuterium [6], or carbon [7]. Here the observed energy deposition does not depend on the neutrino energy as long as it is above threshold. Perhaps neutrino-proton elastic scattering [8] can be detected in KamLAND [7]. This is similar to neutrino-nucleus elastic scattering but has a smaller cross section.

Alternatively, it may be possible to detect ν_x using inelastic excitations of Pb. Proposals include using lead perchlorate, as suggested by Elliott [9], OMNIS [10] and LAND [11]. Here some information on ν_x energies may be obtained by measuring the ratio of single- to two-neutron knockout. However, the inelastic Pb cross sections are somewhat uncertain. In contrast, neutrino-nucleus elastic cross sections can be calculated accurately with very little theoretical uncertainty.

The ν_x spectrum depends on how neutrinos thermalize with matter in a supernova, and is somewhat uncertain. Keil, Raffelt, and Janka have studied the effects of NN bremsstrahlung, pair annihilation, and nucleon recoil on the ν_x spectrum [12]. These effects can be measured with an elastic-scattering detector.

Obtaining direct information on ν_x energies may be very important because the difference in energies for ν_x compared to ν_e or $\bar{\nu}_e$ is the primary lever arm for observing neutrino oscillations. For example, $\nu_x\rightarrow\nu_e$ oscillations could lead to high energy ν_e. However, deducing the oscillation probability may depend crucially on knowing how hot the ν_x were to begin with. Neutrino-nucleus elastic scattering itself is ''flavor blind.'' Therefore, the signal should be independent of neutrino oscillations (among active species). Thus elastic scattering may provide a baseline with which to characterize the supernova source. Comparing this information to other flavor-dependent information and theoretical simulations may provide the best evidence of oscillations.

The kinetic energy of the recoiling nuclei is low, typically below 100 keV. It is difficult to detect such low-energy events in the presence of radioactive backgrounds. Furthermore, scintillation signals from the nuclear recoils may be reduced by quenching because of the very high ionization density. However, recent progress in designing detectors for low-energy solar neutrinos suggests that detection may be

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feasible. In general, backgrounds for solar neutrinos with a low count-rate signal may be more severe than those for a supernova, where all of the events are concentrated in a few-second interval.

Cryogenic Low Energy Astrophysics with Noble gases (CLEAN) is a proposed detector for low-energy solar neutrinos based on scintillation in an ultrapure cryogenic liquid [13]. This will detect electrons from neutrino-electron scattering at energies comparable to the recoil energy of nuclei from supernova neutrinos. In this paper we discuss the utility of CLEAN for supernovae detection via neutrino-nucleus elastic scattering.

There is considerable interest in the direct detection of weakly interacting massive particles (WIMP). These are expected to produce recoiling nuclei with a spectrum somewhat similar [14] to that of supernova neutrino-nucleus elastic scattering. Again, backgrounds for WIMP detection may be larger than for supernovae because of the low WIMP count rates. Present WIMP detectors, for example CDMS [15], have small target masses. However, future detectors may be larger.

It is important to search for neutrinoless double-beta decay, as this can distinguish Dirac from Majorana neutrinos. Existing ^{76}Ge experiments use multikilogram masses [16]. The next-generation experiments such as Majorana [17] or Genius [18] may employ up to a ton of Ge. The need for good energy resolution, to tell neutrinoless from two-neutrino double-beta decay, often aids in the detection of low-energy recoils. We calculate that the largest double-beta decay experiments may soon be sensitive to galactic supernovae via elastic scattering.

Finally, micropattern gas detectors [19] may have a threshold low enough to detect nuclear recoils. This may allow the observation of neutrino-nucleus elastic scattering using reactor antineutrinos.

Thus the technical requirements for detecting low-energy solar neutrinos, WIMP, double-beta decay, and supernovae via nuclear-elastic scattering may be similar. One detector or approach for low-threshold, low-background, large mass measurements may have applications in multiple areas, including supernova detection via neutrino-nucleus scattering.

In Sec. II we fold elastic scattering cross sections with a model supernova neutrino spectrum to produce recoil spectra and yields. We consider a range of noble-gas targets from ^{4}He to ^{132}Xe along with ^{12}C, ^{28}Si, ^{76}Ge, ^{114}Cd, ^{130}Te, and ^{208}Pb. We also discuss extrapolating yields to nearby isotopes. Section III focuses on the liquid-Ne-based CLEAN detector, which appears to be very promising. A Monte Carlo simulation of backgrounds in CLEAN is presented and compared to the expected supernova signal. We discuss the large signal-to-background ratio, choice of fiducial volume, and possible detector thresholds. We conclude in Sec. IV.

II. SUPERNOVA SIGNALS IN VARIOUS DETECTORS

The neutrino-nucleus elastic-scattering cross section $d\sigma/d\Omega$ is [20,3],

$$\frac{d\sigma}{d\Omega}=\frac{G^2}{4\pi^2}k^2(1+\cos\theta)\frac{Q_w^2}{4}F(Q^2)^2, \tag{1}$$

for a neutrino of energy k scattering at angle θ. The Fermi constant is G. This coherent cross section depends on the square of the weak charge Q_w

$$Q_w=N-(1-4\sin^2\Theta_W)Z \tag{2}$$

of a nucleus with N neutrons and Z protons. The weak mixing angle is $\sin^2\Theta_W\approx 0.231$ [21]. We assume a spin-zero target. Finally, the ground-state elastic form factor $F(Q^2)$ at momentum transfer Q,

$$Q^2=2k^2(1-\cos\theta), \tag{3}$$

is

$$F(Q^2)=\frac{1}{Q_w}\int d^3r\frac{\sin(Qr)}{Qr}[\rho_n(r)-(1-4\sin^2\Theta_W)\rho_p(r)]. \tag{4}$$

Here $\rho_n(r)$ is the neutron density and $\rho_p(r)$ is the proton density. The form factor is normalized $F(Q^2=0)=1$. We neglect a small correction from the single-nucleon form factors.

The inclusion of $F(Q^2)$ is crucial for heavier targets. However, we evaluate it at relatively small Q^2 so the exact form of the densities is not important. The proton density is often well constrained by measured charge densities. For simplicity we use theoretical densities from simple relativistic-mean-field calculations using the successful NL3 effective interaction [22]. These calculations assume spherical ground states and do not include pairing corrections. The use of other densities is not expected to change our results significantly.

We now consider a simple "standard model" for the supernova-neutrino spectra, see for example [23]. This model is close to what others have used. A total energy of 3×10^{53} ergs (1 erg$=10^{-7}$ J) is assumed to be radiated in neutrinos from a supernova at a distance d of 10 kpc (3.1×10^{20} m). For simplicity we use Boltzmann spectra at temperatures of $k_BT=3.5$, 5 and 8 MeV for the ν_e, $\bar{\nu}_e$ and ν_x components, respectively. Here k_B is the Boltzmann constant, which we set to one in the rest of the paper. The use of Fermi Dirac spectra (at zero chemical potential) should give similar results. However, neutrino-nucleus elastic scattering is sensitive to the high-energy tails in the spectra. Therefore non-thermal spectra could modify our results somewhat and should be investigated in future work.

We assume equal partition in energy among the ν_e $\bar{\nu}_e$ and the four ν_x components. Therefore this standard supernova radiates a total of $N_{\nu_e}=3.0\times10^{57}$, $N_{\bar{\nu}_e}=2.1\times10^{57}$ and $N_{\nu_x}=5.2\times10^{57}$ neutrinos. The time integral of the neutrino flux at Earth $\phi_i(k)$ for a neutrino of energy k is

$$\phi_i(k)=\frac{1}{4\pi d^2}\frac{N_i}{2T_i^3}k^2\mathrm{e}^{-k/T_i}, \tag{5}$$

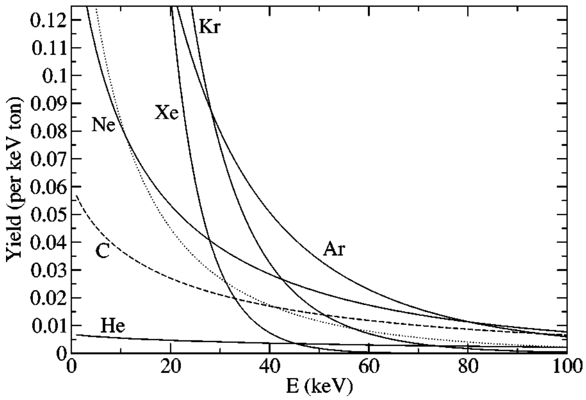

FIG. 1. Yield versus recoil kinetic energy E. The solid curves are for noble targets of ^{4}He, ^{20}Ne, ^{40}Ar, ^{84}Kr and ^{132}Xe as indicated; the dashed curve is for ^{12}C. Finally the dotted curve, only shown for ^{20}Ne, assumes a reduced ν_x temperature of $T_{\nu_x} = 5$ MeV.

for $i=\nu_e$, $\bar{\nu}_e$, or ν_x.

Microscopic simulations of supernovae suggest that equal partition of energy may be good only to $\approx 25\%$. Furthermore, there is important uncertainty in the ν_x spectrum, with estimates of T_{ν_x} ranging from ≈ 6 to 8 MeV. It is an important goal of elastic-scattering detectors to measure T_{ν_x}. Therefore, the predictions of our supernova spectrum have significant uncertainties. Nevertheless, this simple model should provide order-of-magnitude estimates and may allow easy comparisons to other calculations.

The yield of recoiling nuclei with energy E and mass M is

$$Y(E)=2\pi N_t \Sigma_{i=\nu_e,\bar{\nu}_e,\nu_x}\int_0^\infty dk\,\phi_i(k) \times \int_{-1}^{1} d\cos\theta\,\delta\left(E-\frac{Q^2}{2M}\right)\frac{d\sigma}{d\Omega}, \quad (6)$$

where N_t is the total number of target atoms. For our Boltzmann spectra this integral is simple:

$$Y(E)=\frac{G^2}{\pi}\frac{Q_w^2}{4}MF^2(2ME)\left(\frac{N_t}{4\pi d^2}\right)\Sigma_{i=\nu_e,\bar{\nu}_e,\nu_x} \times N_i(t_i+1)\mathrm{e}^{-t_i}, \quad (7)$$

with $t_i=[ME/(2T_i^2)]^{1/2}$. For large recoil energy E, $Y(E)$ is proportional to

$$Y(E)\rightarrow F^2(2ME)\mathrm{e}^{-(M/2T_{\nu_x}^2)^{1/2}E^{1/2}}. \quad (8)$$

For light nuclei the high-energy tail continues to hundreds of keV and is produced by the scattering of very-high-energy ν_x. However, for heavier nuclei the tail is sharply reduced by the nuclear form factor.

We consider first noble-liquid detectors from ^{4}He to ^{132}Xe and then a range of other detectors in order of increasing mass number A from ^{12}C to ^{208}Pb. The yield $Y(E)$ from Eq. (7) is shown in Fig. 1 for detectors made of ^{4}He, ^{20}Ne, ^{40}Ar, ^{84}Kr, and ^{132}Xe. We do not mean to imply that detectors would be feasible with all of these liquids. However, we show these nuclei to illustrate how the yield depends on A for a broad range of A. The spectra in Fig. 1 are peaked at low recoil energy E. Increasing A raises the cross section because coherent scattering is proportional to N^2. Thus at low energies $Y(E)$ increases significantly with A. However, as A increases the spectrum is strongly shifted to lower energies by the form factor and the large target mass. The energy integral of $Y(E)$, or total yield, is given in Table I in events per ton of detector. Also listed are events above a threshold of 5, 10, 25, or 50 keV. Finally, the average recoil energy of the nuclei is given. This average is influenced by a small number of events at high energies, while the spectrum is peaked at low energies.

The optimal choice of A may involve a trade-off between the cross section, which favors high A, and the recoil energy, which favors small A. This choice may depend on the attainable threshold. Furthermore, the choice of target material depends on a host of other practical considerations, including the presence of possible backgrounds from radioactive isotopes. Although ^{4}He has a relatively small cross section it

TABLE I. Yield in events per ton for a supernova at 10 kpc assuming different target materials. Also listed is the number of events above thresholds of 5, 10, 25 or 50 keV. Finally the average recoil energy $\langle E\rangle$ is given.

Target	Y	$Y>5$ keV	$Y>10$ keV	$Y>25$ keV	$Y>50$ keV	$\langle E\rangle$ (keV)
^{4}He	0.85	0.82	0.79	0.72	0.62	240
^{12}C	2.5	2.2	2.0	1.6	1.1	83
^{20}Ne	4.0	3.3	2.9	2.0	1.2	46
^{28}Si	5.5	4.2	3.4	2.1	1.1	31
^{40}Ar	9.4	6.6	5.0	2.5	0.99	21
^{76}Ge	18.6	9.6	5.8	1.7	0.30	9.5
^{84}Kr	19.8	9.5	5.5	1.4	0.20	8.4
^{114}Cd	26.3	9.7	4.6	0.70	0.041	5.7
^{130}Te	31.8	10.1	4.3	0.47	0.014	4.8
^{132}Xe	31.1	9.8	4.1	0.43	0.012	4.8
^{208}Pb	47.5	7.3	1.7	0.022	0.001	2.6

has high recoil energies. We find a total yield in Table I of 0.85 events per ton. Helium-based solar-neutrino detectors include HERON [24] and TPC [25] (or HELLAZ [26]).

Perhaps nuclei near $A=40$ give a reasonable balance between the cross section and the recoil energy. However, Ar may have backgrounds from radioactive ^{39}Ar and ^{42}Ar, while Kr may have backgrounds from ^{85}Kr. Xenon is being used in several dark-matter, double-beta decay and solar-neutrino detectors, including XMASS [27], XENON [28] and ZEPLIN [29]. The total yield is very large, 31 events per ton. However, because ^{132}Xe is heavy, there is a strong premium on obtaining a low threshold. Background from the 2ν double-beta decay of ^{136}Xe should not be a problem for a supernova detector.

Above a threshold of 25 keV the yield is a relatively slow function of A. Therefore one may have considerable freedom in the choice of target material. We consider the CLEAN liquid-Ne solar-neutrino detector [13] at some length. The total yield of 3.99 events per ton is dominated by 3.08 ν_x events with only 0.38 ν_e and 0.53 $\bar{\nu}_e$ events. One is very sensitive to the ν_x spectrum. For example, if the ν_x temperature is not the expected 8 MeV but instead is near that for $\bar{\nu}_e$ $T_x=5$ MeV, the spectrum in Fig. 1 is greatly changed. This verifies that the recoil spectrum contains direct information on the ν_x energies. A Monte Carlo simulation of backgrounds in CLEAN is presented in Sec. III.

We now consider a number of other targets. Detectors based on organic scintillator such as Borexino and KamLAND [30,7] have a yield of 2.50 events per ton of ^{12}C, see Table I. With any carbon-based detector there will be backgrounds from ^{14}C. Borexino should have a ratio ^{14}C/^{12}C of the order 10^{-18} [30]. At a concentration of 10^{-18} there will be about two ^{14}C decays per ton during the 10 sec of a supernova neutrino burst. This is comparable to the number of elastic recoils. However, the ^{14}C background should have a different spectrum and can be well measured at other times. Therefore, this background may not prevent the use of carbon as a supernova detector, even if it does prevent the observation of pp solar neutrinos. Quenching may be a serious problem for organic scintillator. The amount of light produced from recoiling C ions may be much less than that for recoiling electrons [8].

An organic scintillator will also have events from neutrino-proton elastic scattering [8]. We estimate a yield of about 0.33 events per ton of CH_2. Because of the light proton mass these events will have a larger recoil energy. The proton elastic-scattering cross section has a theoretical uncertainty of 10% to 20% from possible strange quark contributions to the nucleon's axial current and spin [31]. It would be very useful to have better laboratory measurements of neutrino-proton elastic scattering. In contrast, strange quarks are not expected to make significant contributions for supernova neutrino-nucleus elastic scattering. Indeed, there is almost no theoretical uncertainty in the neutrino-nucleus elastic cross sections.

Silicon detectors such as those described in [4] have a yield of 5.5 events per ton and the recoil spectrum is shown in Fig. 2, while ^{76}Ge detectors have a yield of 18.6 events per ton and an average recoil energy of 9.5 keV. The double-beta decay experiment Majorana [17] is proposed to have a 500 kg mass, while Genius [18] has a proposed mass of one ton. These detectors should have very low backgrounds and low thresholds. Therefore they should be sensitive to a supernova at 10 kpc. It is remarkable that such small target masses can yield statistics for our own galaxy comparable to those for the historic IMB and Kamiokande signals from SN 1987A in the Large Magellanic Cloud.

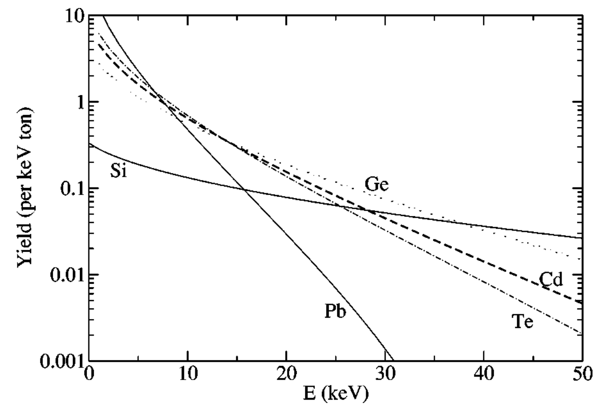

FIG. 2. Yield versus recoil kinetic energy E. The solid curves are for targets of ^{28}Si and ^{208}Pb; the dashed curve is for ^{114}Cd; the dotted curve is for ^{76}Ge; and the dot-dashed curve is for ^{130}Te.

Finally, ^{114}Cd, ^{130}Te and ^{208}Pb yields are listed in Table I. The yield and spectrum for ^{130}Te is very close to ^{132}Xe (see Figs. 1 and 2) since they both have 78 neutrons. The heavy nucleus ^{208}Pb has a very large yield of 47.5 events per ton. However, the average recoil energy is only 2.6 keV. Backgrounds and the need for a very low threshold may make a Pb detector very difficult to build.

The nuclei in Figs. 1 and 2 display a range of recoil spectra. For point nuclei there would be a single universal spectral shape, with the recoil energy decreasing and the yield increasing with increasing A. However, the different nuclear form factors modify the spectra for heavy nuclei.

Finally, we provide a simple formula to extrapolate the yields in Table I to nearby isotopes. If one ignores small changes in the form factors of nearby nuclei, then the yield will be approximately proportional to the square of an effective weak charge, Q_{eff},

$$Q_{eff}^2=\delta_{A,odd}3g_a^2+Q_W^2, \tag{9}$$

with Q_W from Eq. (2), and $\delta_{A,odd}=1$ for odd A nuclei and $\delta_{A,odd}=0$ for even A nuclei. This factor takes into account the axial current of the last nucleon with $g_a=1.26$. Because this term adds in quadrature with Q_W^2, it makes a very small contribution, except for very light systems such as the proton.[1] For example, using Eq. (9) we find that ^{21}Ne and ^{22}Ne have cross sections, respectively, 1.29 and 1.48 times that of ^{20}Ne. Natural Ne is 0.3% ^{21}Ne and 8.8% ^{22}Ne so this will lead to a slight increase in yield over that for pure ^{20}Ne.

[1]We ignore the slightly different angular distribution of this term.

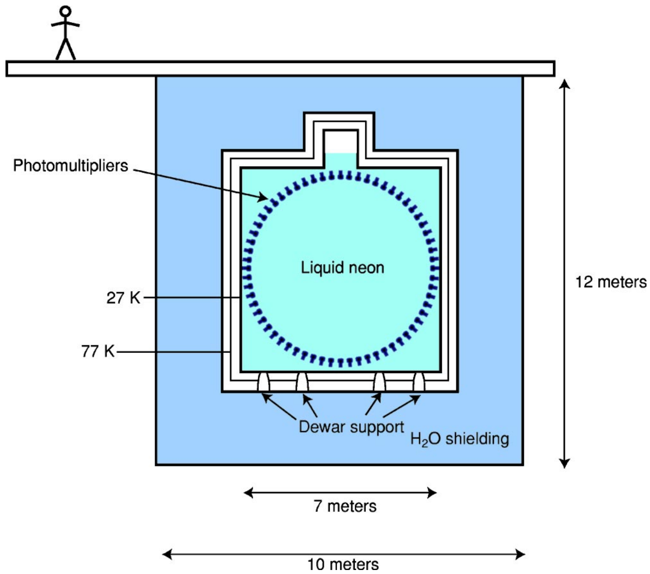

FIG. 3. Diagram of CLEAN.

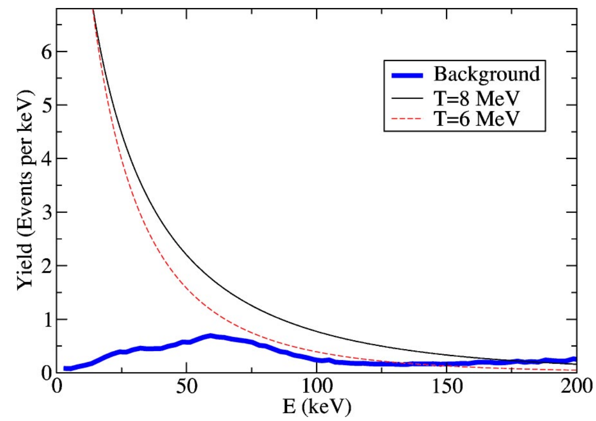

FIG. 4. Yield for full a 100 ton fiducial mass of CLEAN versus recoil kinetic energy E. The solid curve is the expected supernova signal assuming a distance of 10 kpc and a ν_x temperature $T_{\nu_x}=8$ MeV. The dashed curve assumes $T_{\nu_x}=6$ MeV. Finally, the thick curve is the predicted background from the Monte Carlo simulation assuming an observing time of 10 sec.

III. THE CLEAN DETECTOR

CLEAN, a detector concept based on liquid Ne, was originally proposed for the detection of low-energy solar neutrinos. It will also have high sensitivity to weakly interacting massive particles (WIMP). Liquid neon has a high scintillation yield, has no long-lived radioactive isotopes, and can be easily purified using cold traps. In addition, neon is inexpensive, dense, and transparent to its own scintillation light, making it practical for use in a large self-shielding apparatus. Here we consider a CLEAN detector in which a stainless steel tank holds 200 tons of liquid neon, half of which is exposed to a wavelength shifter to convert the ultraviolet light to the visible. Inside the tank and suspended in the liquid neon are several thousand photomultipliers. A diagram of the proposed CLEAN design is shown in Fig. 3.

CLEAN will also be sensitive to supernova neutrinos, detected through neutrino-nuclear scattering. In this case the entire active neon mass inside the wavelength shifter can be used, with a possible modest fiducial volume cut to reduce radioactive backgrounds.

Of prime importance for determining the sensitivity of CLEAN to neutrino-nuclear scattering is the determination of the light yield of liquid neon for nuclear recoils. Because the density of excitation in the scintillator is typically higher for nuclear recoils than for electron recoils, the chemically excited species are more likely to interact, increasing the likelihood that energy will be lost through mechanisms that do not produce light. This quality is often expressed as a "quenching factor," the ratio of light emitted for a nuclear recoil to the light emitted from an electron recoil, per unit deposition energy. While the quenching factor for liquid neon has not yet been measured, we expect it to be similar in magnitude to the quenching factor measured for liquid xenon. Recent (and widely disagreeing) measurements of the liquid xenon quenching factor [32,33] are 22% and 43%. The amount of quenching for liquid neon should be less than that for liquid xenon, as the density (1.2) of liquid neon is less than that of liquid xenon, while the scintillation mechanism in liquid neon is qualitatively similar. For the following simulations, we assume that the quenching factor for liquid neon is 0.25. Clearly the scintillation quenching factor in liquid neon would have to be accurately measured in order to properly interpret any supernova data.

As for all neutrino detectors, a prime design consideration in CLEAN is the reduction of radioactive backgrounds. We expect that any radioactive species suspended in the liquid neon will be removed by passing the neon through charcoal or similar adsorbant; however, there will remain a high rate of gamma rays entering the liquid neon after being emitted by the surrounding photomultipliers, photomultiplier support structure, wavelength shifter, and stainless steel tank containing the liquid neon.

Figure 4 shows the expected supernova neutrino recoil spectrum for a CLEAN detector with 100 tons of active liquid neon, assuming 3750 scintillation photons per MeV, 100% efficiency for the wavelength shifter, photomultiplier coverage of 75%, and a photomultiplier quantum efficiency of 15%. Also shown is the expected radioactive background for 10 sec of observing time, assuming that the combined gamma and x-ray emission is dominated by the photomultiplier glass and the wavelength shifter substrate. The simulation assumes photomultipliers 20 cm in diameter, each with mass 650 g, with 30 ng per g of U and Th and 60 μg per g of K in the glass. The wavelength shifter is assumed to be evaporated on quartz wafers of 1 mm thickness, with a U and Th concentration of 1 ng per g. From 10^4 sec of simulated data, we find a background of 62 ± 8 events in 10 sec within the energy range of 0 to 200 keV. Here the uncertainty corresponds to the ±1-sigma interval for a particular 10-sec observation. Since liquid neon has no long-lived radioactive isotopes that would limit its practical threshold, the CLEAN detector could conceivably trigger on as few as two photoelectrons. The accidental coincidence rate in CLEAN will be low, as the photomultiplier dark count rate will be suppressed at liquid-neon temperature (27 K). Thus we expect that the

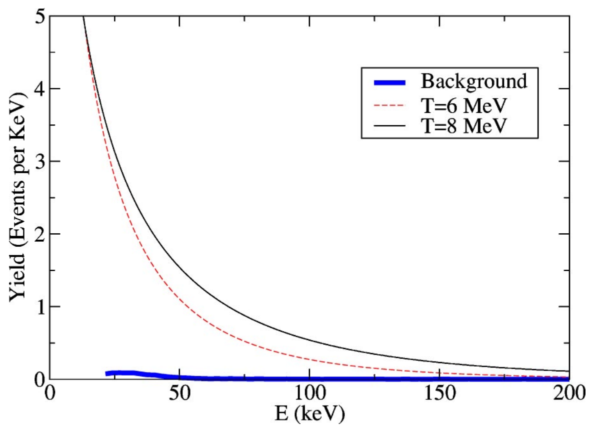

FIG. 5. Yield for 70 ton fiducial mass of CLEAN versus recoil kinetic energy *E*. The solid curve is the expected supernova signal assuming a distance of 10 kpc and a ν_x temperature $T_{\nu_x}=8$ MeV. The dashed curve assumes $T_{\nu_x}=6$ MeV. Finally, the thick curve is the predicted background from the Monte Carlo simulation assuming an observing time of 10 sec.

full 100 tons of liquid neon could be viewed with a threshold of 2 photoelectrons, equivalent to a recoil energy of about 5 keV. The expected 62 background events is smaller than the expected supernova signal of 330 Ne elastic events above 5 keV in 100 tons.

The radioactive backgrounds, while small in comparison to the supernova signal, can be lowered further through position resolution, since most gamma rays will deposit their energy in the outer edges of the liquid neon sphere. Recently, Monte Carlo simulations have shown that the location of ionizing radiation events in CLEAN can be determined by analyzing the pattern of photomultiplier hits. These simulations are described in detail in an upcoming publication [34]. Here we show only some results relevant to supernova neutrino detection. We find that a mild fiducial radius cut, leaving a mass of 70 tons, virtually eliminates gamma-ray background for the purposes of supernova neutrino detection (only 2.6 ± 1.6 events in the fiducial volume in 10 sec). These results are shown in Fig. 5. In the case of a fiducial volume cut, detecting a few more photoelectrons will improve the convergence of the position resolution algorithm. Currently we can analyze events that produce as few as 8 photoelectrons (recoil energy of 21 keV) if position cuts are applied. In general, as the position cut is increased or the number of photoelectrons is reduced, algorithm convergence should be carefully checked. The expected 2.6 background events are much smaller than the expected supernova signal of 140 Ne events above 21 keV in 70 tons.

The signal-to-noise ratio reported here, though already quite large, might be significantly improved by the development of photomultipliers with lower inherent radioactivity. Such photomultipliers are under investigation by the CLEAN and XENON Collaborations. In addition, plans are being made to measure the quenching factor for nuclear recoils in liquid neon, as this measurement is important for the determination of the sensitivity of CLEAN to WIMP particles, as well as for supernova neutrinos.

A great advantage of elastic detectors is their energy information from the nuclear recoils. The recoil spectra in Figs. 4 and 5 show a large difference between ν_x temperatures of 6 and 8 MeV. This verifies the large sensitivity to ν_x energies. We now speculate on how well CLEAN could measure the ν_x spectrum.

The large number of events, ≈ 330, relatively low background and low threshold, 5 keV, in Fig. 4 suggests that CLEAN could determine a single parameter with a statistical accuracy of almost 5%. For example, the background rate in Fig. 4 of 62 events in 10 sec will be well measured at other times. Therefore, it will only contribute a statistical uncertainty of $\pm 62^{1/2}\approx 8$ events or 2% which is negligible.

Perhaps one is most interested in trying to extract two parameters: information on the ν_x flux and information on the ν_x spectrum. Clearly the error in extracting two parameters will be larger then that for a single parameter. Nevertheless, the large number of events in Fig. 4 and the strong dependence of the recoil spectrum on T_{ν_x} suggests that T_{ν_x} can still be extracted well, perhaps with an error of 10% to 20%. Furthermore, other ''energy blind'' neutral current detectors such as SNO and Super-K could provide additional information to help fix the ν_x flux. These detectors observe ν_x via deuteron breakup or ^{16}O excitation without direct information on T_{ν_x}. Of course, when combining detectors one needs to worry about different systematic errors.

We have not yet performed detailed fits to determine how well T_{ν_x} can be extracted. There are a number of uncertainties. Changes in the supernova distance or achievable threshold will impact the statistics. Furthermore, if the background is much larger than shown in Fig. 4 one may need to make position cuts, such as in Fig. 5, further reducing statistics. The supernova spectrum need not be thermal. Perhaps it is best to fit for an average ν_x energy instead of a temperature. The relatively low threshold, 5 keV, in Fig. 4 may simplify the determination of an average energy. Finally, there are contributions from $\bar{\nu}_e$ and ν_e. We assume that the $\bar{\nu}_e$ flux and spectrum will be measured in Super-K, allowing its contribution to be accurately determined. We also expect the ν_e contribution to be small because of its low temperature. Note, Figs. 4 and 5 show the effects of changing just T_{ν_x} while keeping $T_{\bar{\nu}_e}$ and T_{ν_e} fixed.

For a supernova at 10 kpc, CLEAN should be able to easily distinguish if T_{ν_x} is close to 8 MeV, as expected in some original simulations, or if T_{ν_x} is close to 5 MeV, which is expected for $T_{\bar{\nu}_e}$. This will show if the $\bar{\nu}_e$ spectrum can contain any realistic information on $\bar{\nu}_x\rightarrow\bar{\nu}_e$ oscillations. Furthermore, it may be crucial in using the ν_e spectrum to extract quantitative information on $\nu_x\rightarrow\nu_e$ oscillations.

IV. CONCLUSIONS

Detectors with reduced radioactive backgrounds may be able to study supernovae via neutrino-nucleus elastic scattering. This could provide important information on the flux and spectrum of ν_x (ν_μ and ν_τ). Elastic-scattering detectors could see a few or more events per ton for a supernova at 10 kpc. This is 20 or more times the number of events per ton of existing water detectors. The CLEAN experiment, based on the detection of scintillation in liquid Ne, is a prime example of a detector that would be sensitive to the elastic scattering of supernova neutrinos. Its active mass of 100 tons may yield almost 400 ν_x events. In addition, many other detectors, including the largest dark-matter and double-beta decay experiments, may also be sensitive to supernova neutrinos via elastic scattering.

Observation of neutrino-nuclear elastic scattering will complement supernova signals from other detectors. Water detectors such as SNO or Super-K will detect ν_x without ν_x spectral information. This energy information could be important for neutrino oscillations. KamLAND may be able to measure ν-p elastic scattering. This contains energy information just like ν-A scattering. The small cross section for ν-p scattering may be compensated by a large detector mass. This may yield only slightly smaller statistics than CLEAN. We strongly encourage development of detectors based on both ν-p and ν-A elastic scattering since they may have different backgrounds, thresholds, and systematic errors. Furthermore, the very large $\nu-A$ elastic cross sections may allow even larger statistics in future detectors.

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